Analysis of the performance characteristics of the five-channel Microtops II sun photometer for measuring Aerosol Optical Thickness and Precipitable Water Vapor.

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ABSTRACT

Five Microtops II sun photometers were studied in detail at the NASA Goddard Space Flight Center (GSFC) to determine their performance in measuring aerosol optical thickness (AOT or $\tau_{a\lambda}$) and precipitable column water vapor (W). Each derives $\tau_{a\lambda}$ from measured signals at four wavelengths λ (340, 440, 675, and 870 nm), and W from the 936 nm signal measurements. Accuracy of $\tau_{a\lambda}$ and W determination depends on the reliability of the relevant channel calibration coefficient (V_0). Relative calibration by transfer of parameters from a more accurate sun photometer (such as the Mauna-Loa-calibrated AERONET master sun photometer at GSFC) is more reliable than Langley calibration performed at GSFC. It was found that the factory-determined value of the instrument constant for the 936 nm filter (k= 0.7847) used in the Microtops' internal algorithm is unrealistic, causing large errors in $V_{0(936)}$, τ_{a936}, and W. Thus, when applied for transfer calibration at GSFC, whereas the random variation of V_0 at 340 to 870 nm is quite small, with coefficients of variation (CV) in the range of 0 to 2.4%, at 936 nm the CV goes up to 19%. Also, the systematic temporal variation of V_0 at 340 to 870 nm is very slow, while at 936 nm it is large and exhibits a very high dependence on W. The algorithm also computes τ_{a936} as 0.91 τ_{a870}, which is highly simplistic. Therefore, it is recommended to determine τ_{a936} by logarithmic extrapolation from τ_{a675} and τ_{a870}. From the operational standpoint of the Microtops, apart from errors that may result from unperceived cloud contamination, the main sources of error include inaccurate pointing to the Sun, neglecting to clean the front quartz window, and neglecting to calibrate correctly. If these three issues are adequately taken care of, the Microtops can be quite accurate and stable, with root mean square (rms) differences between corresponding retrievals from clean calibrated Microtops and the AERONET sun photometer being about ±0.02 at 340 nm, decreasing down to about ±0.01 at 870 nm.

1 INTRODUCTION

Aerosols are an enigmatic yet indispensable component in global climate studies and modeling. The physical characteristics, composition, abundance, and spatial distribution and dynamics of aerosols are still very poorly known. Aerosol spectral optical thickness (AOT or $\tau_{a\lambda}$) and precipitable water vapor amount (W) are two very important physical parameters for characterizing aerosols. Routine observation of total atmospheric column AOT and W globally is a fundamental way of determining aerosol optical characteristics and its influence in the global radiation budget and climate change. The most practical means of making these observations is by remote sensing, which can be either from the ground (looking in the skyward direction with sun photometers) or from space (looking towards the ground through the atmosphere with imaging radiometers onboard satellites or high altitude aircraft).

Ground-based and satellite remote sensing of AOT and W have different but complementary characteristics. Ground-based observations enable the acquisition of data as many times as possible in one day, but only for individually discrete locations. On the other hand, satellite observations can cover more extensive areas of the earth (even the whole earth) in one day, though only one or two observations can be made on a given position each day. Ground and satellite observations are vital for different situations as well as for cross-validating each other.

A number of currently available operational satellite sensors (for example, AVHRR, TOMS, and more recently MODIS) provide data for retrieving aerosol optical properties. On the other hand, there are a number of networks of ground-based sun-photometers measuring AOT and W at different locations around the world. One such prominent network is the AERosol RObotic NETwork (AERONET) comprising a series of automatic tracking sun-photometers currently occupying more than 100 locations in different parts of the world [*Holben et al.*, 1998; *Holben et al.*, 2001]. Data acquired by AERONET instruments are very widely used by the aerosol community for different kinds of studies and modeling, as well as for the validation of satellite retrievals [*Goloub et al.*, 1999; *Zhao et al.*, 2001]. Specifically, AERONET data is used intensively for the validation of aerosol parameter retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra Satellite launched on 18 December 1999 [*Chu et al.*, 2001; *Ichoku et al.*, 2001; *Remer et al.*, 2001]. However, AERONET sun-photometers cannot be located everywhere and every time AOT and *W* data are needed, such as during some field campaigns and other special events, as well as for routine measurements applied to certain specific studies. Therefore, there is great need for alternative (especially portable and low-cost) sun photometers for such purposes.

One of such sun photometers, which has been used quite widely in recent times is the MICROTOPS II Sun photometer manufactured by the Solar Light Company, Philadelphia, U.S.A. It is relatively affordable, portable, and easy to operate, and is convenient for all the purposes mentioned above. In fact, MICROTOPS II has two versions: (i) the 'ozone monitor' or 'ozonometer' adapted to column ozone measurement and, (ii) the 'Sun photometer' designed for aerosol optical thickness measurements. Either one can be configured by the manufacturer to measure water vapor column thickness *W. Morys et al.* [2001] gave a general description of the MICROTOPS II instrument design, calibration and performance, but focused the discussion on the ozonometer type. Although, they discussed the water vapor retrieval aspects, they admitted that 'the column water vapor measurements by MICROTOPS II have yet to be fully analyzed' [*Morys et al.*, 2001, p. 14,581]. *Porter et al.* [2001] examined the use of the sun photometer version of the MICROTOPS II onboard ship platforms, and possible effects of instability caused by ship motion on the measurement accuracy. However, their instruments do not include the 936 nm (water vapor absorption) channel, and does not measure *W*. Therefore, it has become imperative to fully characterize the Microtops II sun photometer in order to determine its reliability in acquiring $\tau_{a\lambda}$ and W data, especially for use in satellite data validation. This is the objective of this study.

2 INSTRUMENT DESCRIPTION AND OPERATION

The Microtops II Sun photometer is a portable instrument, measuring 10 cm by 20 cm by 4.3 cm, and weighing only 600 grams [*Morys et al.*, 2001]. It is designed for use as a hand-held manually operated instrument. The physical and operational characteristics of the instrument are detailed in the "User's Guide", which is publicly accessible on the internet (http://www.solar.com/manuals.htm). The Sun photometer measures solar radiance in five spectral wavebands from which it automatically derives AOT. The five wavelengths may be specified while ordering the instrument, such that appropriate filters are custom designed and installed by the manufacturer.

In this study, five Microtops II Sun photometers (serial numbers: 3761, 3762, 3763, 3760, and 3657) of exactly the same type have been used. Each has five channels with peak wavelengths, λ, of 340, 440, 675, 870, and 936 nm. The filters used in all channels have a peak wavelength precision of ±1.5 nm, and a full width at half maximum (FWHM) band pass of 10 nm (http://www.solar.com/sunphoto.htm). It is pertinent to mention that the 936 nm wavelength is greatly affected by water vapor absorption. As such, the most significant parameter used to derive W in the instruments is the 936 nm signal data.

At 340, 440, 675 and 870 nm wavelengths, AOT is derived based on the Beer-Lambert-Bouguer law as follows:

$$V_\lambda = V_{0\lambda} D^{-2} \exp(-\tau_\lambda M) \quad (1)$$

where, for each channel (wavelength),

V_λ = the signal measured by the instrument at wavelength λ,

$V_{0\lambda}$= the extraterrestrial signal at wavelength λ,

D = Earth-Sun Distance in Astronomical units at time of observation,

τ_λ = total optical thickness ($\tau_\lambda = \tau_{a\lambda} + \tau_{R\lambda} + \tau_{O3\lambda}$) at wavelength λ,

$\tau_{a\lambda}$ = aerosol optical thickness (AOT) at wavelength λ,

$\tau_{R\lambda}$ = Rayleigh (air) optical thickness at wavelength λ,

$\tau_{O3\lambda}$ = Ozone optical thickness at wavelength λ,

M = the optical air mass

Because of the nonlinear contribution from water vapor in the 936 nm channel, the equivalent equation for this channel is given by [e.g. *Reagan et al.*, 1995]:

$$V_w = V_{0w} D^{-2} \exp[-\tau_w M - k(WM)^b] \tag{2}$$

where,

V_w, V_{0w}, D, τ_w, and M remain as defined in equation (1), except that subscript w is used to designate the 936 nm water vapor absorption channel.

W = vertical water vapor column thickness

k and b are instrument constants numerically derived for the 936 nm filter.

The Rayleigh and Ozone optical thicknesses, τ_R and τ_{O3}, are obtained from atmospheric models:

$$\tau_{R\lambda} = R_4 \exp(-h / 29.3 / 273) \tag{3}$$

$$\tau_{O3\lambda} = Ozabs * DOBS / 1000 \tag{4}$$

where,

h = altitude of the place of observation in meters

$R_4 = 28773.6 * (R_2 * (2 + R_2) * \lambda^{-2})^2$

$R_2 = 10^{-8} * \{8342.13 + 2406030 / (130 - \lambda^{-2}) + 15997 / (38.9 - \lambda^{-2})\}$

λ= wavelength in microns

(For further information on $\tau_{R\lambda}$ computation, see e.g., *Edlén* [1966], *Teillet* [1990], and *Bodaine et al.* [1999])

Ozabs = Ozone absorption cross section, extracted from a lookup table based on wavelength [e.g. *Molina and Molina*, 1986, *Vigroux*, 1953],

DOBS = Ozone amount in Dobson units, extracted from a lookup table based on latitude and date of observation [e.g. *London, et al.*, 1976].

The precipitable water vapor column thickness W is evaluated by combining equations (1) and (2), and making W the subject of the resulting equation [e.g. *Morys et al.*, 2001]. As described in the MICROTOPS II User's Guide [*Solar Light Company*, 2000], the derivation of AOT in the Microtops instruments does not take into account the Ozone component of the optical thickness. It assumes that this effect is negligible. Table 1 shows a listing of $\tau_{R\lambda}$ and *Ozabs* computed for our place of observation, which has an elevation of about 50 m above sea level. It is obvious that $\tau_{R\lambda}$ is quite substantial, especially in the lower wavelengths. Also, given that the values of *DOBS* range between 240 and 440, substituting it in equation (4) would yield $\tau_{O3\lambda}$ values of the order of 30% of the *Ozabs* values in Table 1. Although the $\tau_{O3\lambda}$ values are small, they are certainly not negligible, especially at 340 and 675 nm wavelengths.

The omission of Ozone corrections in the Microtops computation of AOT is one reason to study the instrument measurement characteristics and calibration requirements. Another reason is that, in the Microtops, τ_w (i.e. τ_{a936}) is computed as 0.91 τ_{a870} even though it is acknowledged in the user's guide that equation (2) is the appropriate relationship. Furthermore, any errors that may be incurred from these two inadequate computations would likely propagate into the evaluation of W. All these provide solid justifications for a detailed study of the instrument.

3 METHODOLOGY

3.1 Experimental Design

Several Microtops II sun photometers are currently used in the various aerosol-related projects at the National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC), Greenbelt, Maryland. The instruments are from time to time deployed in the field for data acquisition when necessary in different parts of the world. Most of the data is intended for use in validating aerosol retrievals from MODIS and other satellite sensors. To achieve reliable validation, it is imperative to know the performance characteristics of each instrument. As such, a series of measurements have been conducted occasionally at GSFC with these instruments since 1997 alongside a reference instrument, which is the master automatic tracking Sun photometer/sky radiometer (CIMEL Electronique 318A) belonging AERONET [*Holben, et al.*, 1998]. In its regular operational mode, approximately every 15 minutes during the daytime, the AERONET master sun photometer in GSFC takes direct sun measurements from which it derives $\tau_{a\lambda}$ (at 340, 380, 440, 500, 670, 870, and 1020 nm wavelengths) and W. It also takes sky radiance measurements hourly for computing certain other aerosol parameters such as size distribution. For sun measurements, the AERONET master instrument at GSFC is regularly calibrated by Langley plots at the pristine mountaintop of the National Oceanic and Atmospheric Administration (NOAA) Observatory at Mauna Loa (MLO), Hawaii, and for sky measurements it is calibrated in the laboratory (with a standard integrating sphere). The MLO-calibrated GSFC AERONET master sun photometer is adopted as a standard to calibrate many other sun photometers, including identical types deployed at other locations around the world [*Holben, et al.*, 1998, *Holben, et al.*, 2001]. It is therefore used for calibrating most Microtops sun photometers used by GSFC scientists, and is hereafter referred to as the "reference sun photometer", "AERONET master sun photometer", or simply as "AERONET".

3.2 Microtops II Sun Photometer Measurements

For this study Microtops II Sun photometer measurements were conducted alongside and concurrently with the reference sun photometer. During the measurement sessions, each Microtops was used to take a sequence of measurements in quick succession each time the AERONET sun photometer rises to take its measurements. This is to evaluate the consistency of the Microtops' measurements, as well as to ensure that one or more of the sequence of measurements is as close in time as possible to the actual moment of the AERONET sun photometer measurement.

Microtops' measurements are always taken with great care at GSFC to meet high standards for use in calibration against the AERONET master sun photometer. First of all, to avoid cloud contamination, Microtops measurements are conducted on days that are as cloud-free as possible, and in any case, when there is no cloud patch covering or even close to the line of sight to the Sun. In fact, all effort is made to maintain at least an angular distance of 30° between the Sun and the closest cloud patch. When possible, measurements are conducted around the local solar transit time (local solar noon) in order to limit the effect of optical distortions due to large solar zenith angles, except when intended for use in obtaining Langley plots as described below. The instruments are operated by persons that have undergone proper orientation beforehand in order to minimize human errors from inaccurate pointing to the Sun. Tests conducted with some of the Microtops revealed that bad pointing to the Sun can erroneously increase the AOT values considerably. The Microtops sun-centering view window has cross hairs and two concentric circles, all having a common center. Appropriately, if the optics of the Microtops is completely without fault, when centered, the Sun's center should coincide with the center of the cross hairs and should lie completely inside the inner circle. To test the sensitivity of the instrument to Sun-pointing, the Sun was centered on the circumference of each of the two circles, at the four points where each circle is intersected by a cross hair. Two Microtops sun photometers (serial numbers 3761 and 3762) were used in this test. At the time of the test, with correct Sun centering the average value of τ_{a870} was 0.06, but when the Sun was deliberately centered at the intersections of the cross-hair and the inner circle the average τ_{a870} was 0.9, while for the outer circle it was 3.0. This shows that centering the Sun's image away from the optical axis of the instrument increases AOT error in an exponential fashion. However, it could be possible that when the instrument optics is faulty, the center indicated by the cross hairs and circles may be shifted slightly with respect to the true center. Also, being a hand-held instrument, constancy in centering cannot always be achieved, especially when in a moving platform such as a ship [*Porter et al.*, 2001]. For this reason, it is always advisable to take many measurements in quick succession so as to retain only those corresponding to the smallest AOT values, as these would represent measurements from the most accurate Sun pointing.